CROP GROWTH MODELING AND ITS APPLICATIONS IN AGRICULTURAL METEOROLOGY

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Abstract: This paper discusses various crop growth modeling approaches viz. Statistical, Mechanistic, Deterministic, Stochastic, Dynamic, Static and Simulation etc. Role of climate change in crop modeling and applications of crop growth models in agricultural meteorology are also discussed. A few successfully used crop growth models in agrometeorology are discussed in detail.

INTRODUCTION

Crop is defined as an “Aggregation of individual plant species grown in a unit area for economic purpose”.

Growth is defined as an “Irreversible increase in size and volume and is the consequence of differentiation and distribution occurring in the plant”.

Simulation is defined as “Reproducing the essence of a system without reproducing the system itself”. In simulation the essential characteristics of the system are reproduced in a model, which is then studied in an abbreviated time scale.

A model is a schematic representation of the conception of a system or an act of mimicry or a set of equations, which represents the behaviour of a system. Also, a model is “A representation of an object, system or idea in some form other than that of the entity itself”. Its purpose is usually to aid in explaining, understanding or improving performance of a system. A model is, by definition

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"A simplified version of a part of reality, not a one to one copy". This simplification makes models useful because it offers a comprehensive description of a problem situation. However, the simplification is, at the same time, the greatest drawback of the process. It is a difficult task to produce a comprehensible, operational representation of a part of reality, which grasps the essential elements and mechanisms of that real world system and even more demanding, when the complex systems encountered in environmental management (Murthy, 2002).

The Earth's land resources are finite, whereas the number of people that the land must support continues to grow rapidly. This creates a major problem for agriculture. The production (productivity) must be increased to meet rapidly growing demands while natural resources must be protected. New agricultural research is needed to supply information to farmers, policy makers and other decision makers on how to accomplish sustainable agriculture over the wide variations in climate around the world. In this direction explanation and prediction of growth of managed and natural ecosystems in response to climate and soil-related factors are increasingly important as objectives of science. Quantitative prediction of complex systems, however, depends on integrating information through levels of organization, and the principal approach for that is through the construction of statistical and simulation models. Simulation of system's use and balance of carbon, beginning with the input of carbon from canopy assimilation forms the essential core of most simulations that deal with the growth of vegetation.

Systems are webs or cycles of interacting components. Change in one component of a system produces changes in other components because of the interactions. For example, a change in weather to warm and humid may lead to the more rapid development of a plant disease, a loss in yield of a crop, and consequent financial adversity for individual farmers and so for the people of a region. Most natural systems are complex. Many do not have boundaries. The bio-system is comprised of a complex interaction among the soil, the atmosphere, and the plants that live in it. A chance alteration of one element may yield both desirable and undesirable consequences. Minimizing the undesirable, while reaching the desired end result is the principle aim of the agrometerologist. In any engineering work related to agricultural meteorology the use of mathematical modeling is essential. Of the different modeling techniques, mathematical modeling enables one to predict the behaviour of design while keeping the expense at a minimum. Agricultural systems are basically modified ecosystems. Managing these systems is very difficult. These systems are influenced by the weather both in length and breadth. So, these have to be managed through systems models which are possible only through classical engineering expertise.

TYPES OF MODELS

Depending upon the purpose for which it is designed the models are classified into different groups or types. Of them a few are :

a. Statistical models: These models express the relationship between yield or yield components and weather parameters. In these models relationships are measured in a system using statistical techniques (Table 1).

   Example: Step down regressions, correlation, etc.

b. Mechanistic models: These models explain not only the relationship between weather parameters and yield, but also the mechanism of these models (explains the relationship of influencing dependent variables). These models are based on physical selection.

c. Deterministic models: These models estimate the exact value of the yield or dependent variable. These models also have defined coefficients.

d. Stochastic models: A probability element is attached to each output. For each set of inputs different outputs are given alongwith probabilities. These models define yield or state of dependent variable at a given rate.

e. Dynamic models: Time is included as a variable. Both dependent and independent variables are having values which remain constant over a given period of time.

f. Static: Time is not included as a variables. Dependent and independent variables having values remain constant over a given period of time.

g. Simulation models: Computer models, in general, are a mathematical representation of a real world system. One of the main goals of crop simulation models is to estimate agricultural production as a function of weather and soil conditions as well as crop management. These models use one or more sets of differential equations, and calculate both rate and state variables over time, normally from planting until harvest maturity or final harvest.

Table 1. Prediction models for crop growth, yield components and seed yield of soybean genotypes with meteorological observations

	GENOTYPE	
	MACS-201	MACS-58
Plant height	-89.98+0.77 MAT_1 +0.39 SS_2 -1.10 MIT_3 +12.91 MT_3 -12.50 GDD_3 -0.09 HTU_3 R^2 = 0.97	57.60-0.24 MIT_1 -0.06 RH_{12} -0.07 HTU_3 R^2 = 0.92
Branches per plant	2.97+0.08 SS_1 +0.08 MAT_2 -0.01 HTU_2-0.07 MAT_3 R^2 = 0.91	6.44-0.01 RH_{21} +0.03 MAT_2 -0.12 MAT_3 R^2 = 0.83
Green leaves	-1.20-0.20 MT_1 -0.03 RH_{11} +0.19 GDD_2 -0.18 RH_{13} +0.13 RH_{23} +2.92 MT_3 -3.55 GDD_3 R^2 = 0.98	19.95-0.29 MIT_2 -0.05 RH_{12} -0.60 SS_3 R^2 = 0.78
Leaf area (dm^2 m^{-2})	754.01-25.97 SS_1 -20.65 MAT_2 -29.85 SS_2 +0.15 HTU_2 -23.23 MIT_3 -5.66 RH_{13} -0.73 RH_{23} R^2 = 0.99	451.89-2.28 RH_{11} -7.06 SS_1 -1.90 MIT_2 +1.02 RH_{22} +1.34 HTU_2-2.04 GDD_3 R^2 = 0.99
Leaf area index	-13.46+0.40 SS_1 -0.09 MAT_2 +0.17 MAT_3 +0.15 RH_{23} +1.02 SS_3 -0.02 HTU_3 R^2 = 0.98	18.30-0.03 RH_{11} -0.03 RH_{21} -0.02 HTU_1 +0.02 HTU_2 -0.35 MAT_3 R^2 = 0.96
Canopy dry weight	-1610.10+3.16 RH_{11} +16.65 MT_1 +2.73 HTU_2 +76.04 MAT_3 -6.77 RH_{13} +126.81 SS_3 -14.12 HTU_3 R^2 = 0.99	2018.40-7.14 RH_{11} -2.21 HTU_1 -1.74 RH_{12} -16.14 MAT_3 R^2 = 0.94
No. of pods per plant	-697.79+4.14 MIT_1 +0.94 RH_{11} +13.01 SS_1 +11.14 MAT_3 +2.20 RH_{23} +29.93 SS_3 -1.65 HTU_3 R^2 = 0.99	56.89+3.86 SS_1-0.33 HTU_3 R^2 = 0.88
Seeds per pod	-5.08 + 0.03 MAT_1 + 0.94 RH_{11} +0.05 MIT_2 -0.03 RH_{13} +0.04	4.13-0.07 MIT_1 -0.02 GDD_1 -0.86 GDD_3 R^2 = 0.95 RH_{23} +0.11 SS_3 -0.07 GDD_3 R^2 = 0.99
100 seed weight	3.18-0.05 RH_{11} -0.09 GDD_2 +1.95 MT_3 -2.34 GDD_3 R^2 = 0.93	15.32-0.11 RH_{11} -0.06 RH_{21} -0.10 HTU_1 -0.04 RH_{22} +0.02 HTU_2 +0.74 MT_3 -1.24 GDD_3 R^2 = 0.97
Harvest index	56.16 +0.11 RH_{11} -0.13 RH_{21} +0.38 MAT2 -0.07 HTU_2 -0.69 MAT_3 R^2 = 0.94	151.36-0.20 RH_{11} -0.06 RH_{21} -0.10 HTU_1 -0.63 MAT_2 +0.17 HTU_2 -2.30 MAT_3 -0.06 RH_{13} R^2 = 0.98
Yield	6370.20-7.73 RH_{21} -5.57 HTU_2 -93.85 MAT_3 R^2 = 0.93	6899.70-21.84 RH_{11} -62.83 MT_1-10.89 HTU_3 R^2 = 0.95
Plant height	42.38+0.70 SS_1 -0.07 HTU_3 R^2 = 0.92	110.89-0.36 MIT_1-0.05 RH_{21} +0.042 HTU_1 -0.11 RH_{12} -0.03 RH_{22} -0.01 HTU_2 -0.91 MAT_3 -0.12 RH_{13}-1.1 SS_3 R^2 = 0.99

	GENOTYPE	
	MACS-201	MACS-58
Branches per plant	6.31-0.01 RH_{12} +0.02 MT_2 -0.09 MAT_3 R^2 = 0.91	5.79-0.01 RH_{12} -0.01 RH_{22} -0.06 MAT_3 R^2 = 0.81
Green leaves	2.81+0.68 MAT_1 -0.05 RH_{21} -0.04 HTU_1 -0.25 MIT_2 -0.23 MAT_3 R^2 = 0.77	28.68-0.72 RH_{21} +0.05 SS_1 -0.73 MIT_2 +0.01 RH_{12} -0.48 SS_2 +0.67 GDD_2 -0.05 RH_{13} -0.72 SS_3 -0.27 GDD_3 R^2 = 0.99
Leaf area (dm^2 m^{-2})	190.28-2.01 RH_{11} +1.02 RH_{21} -6.68 SS_1 -4.98 MAT_2 +1.19 HTU_2 +26.48 MT_3 -40.32 GDD_3 R^2 = 0.99	346.96-0.20 RH_{21} +0.02 HTU_1 -0.53 RH_{12} -0.32 RH_{22} +0.013 HTU_2 +1.16 MIT_3 -0.64 RH_{13} -3.80 SS_3 -10.10 GDD_3 R^2 = 0.99
Leaf area index	17.47-0.01 RH_{21} -0.25 SS_1 -0.02 HTU_1 -0.36 MAT_2 +0.06 HTU_2 -0.35 MAT_3 +0.06 RH_{23} +0.39 SS_3 R^2 = 0.99	6.21-0.02 RH_{22} -0.02 HTU_3 R^2 = 0.87
Canopy dry weight	751.46+19.21 MIT_1 -4.19 RH_{11} -2.16 HTU_1 -18.80 MAT_2 +1.47 RH_{12} +4.36 HTU_2 +70.36 SS_3 -4.71 HTU_3 R^2 = 0.99	1568.40-5.00 MAT_1 -6.30 RH_{11} -0.91 HTU_1 +2.20 MAT_2 +0.80 MT_2 +5.40 GDD_2 +0.49 HTU_2 +2.68 RH_{13} -14.91 SS_3 -22.65 MJ_1 R^2 = 0.99
No. of pods per plant	152.48-0.25 RH_{21} -0.28 RH_{12} +0.01 HTU_2 -0.05 MAT_3 -1.24 MIT_2 R^2 = 0.89	56.54+3.39 MAT_1 +6.44 SS_1 +2.80 MT_2 -0.70 HTU_1 -0.53 RH_{12} -0.72 RH_{13} -0.32 HTU_3 R^2 =0.98
Seeds per pod	4.93-0.00 HTU_1 -0.01 RH_{12} +0.01 HTU_2 -0.05 MAT_3 R^2 = 0.86	4.99-0.01 MIT +0.01 RH_{11} +0.06 GDD_1 +0.01 MAT_2 -0.01 RH_{12} -0.04 HTU_2 -0.02 MAT_3 -0.03 RH_{13} +0.02 RH_{23} R^2 = 0.99
100 seed weight	15.45+0.06 MAT_2 -0.28 GDD_3 R^2 = 0.90	28.08-0.12 MAT_1 -0.02 RH_{11} -0.03 RH_{21} +0.01 MAT_2 -0.02 RH_{12} +0.02 RH_{23} -0.45 SS_3 -0.44 GDD_3 +0.02 HTU_3 R^2 = 0.99
Harvest index	44.25+1.10 SS_1 -0.10 HTU_3 R^2 = 0.92	58.90 +1.02 MAT_1 -0.07 RH_{21} -0.10 HTU_1 -0.11 RH_{22} -0.31 SS_{22} -0.62 GDD_2 -0.65 MAT_3 -0.32 GDD_3 R^2 = 1.000
Yield	6373.5-128.52 MAT_3 R^2 = 0.90	7115.90-27.53 MIT_1 -22.21 RH_{11} -4.51 HTU_1 -3.22 RH_{12} -3.00 HTU_2 -66.31 MAT_3 -7.45 HTU_3 R^2 = 0.99

GENOTYPE -MACS-330	
Plant height	85.15-0.67 MAT_1 +0.77 SS_1 -1.10 MAT_2 -0.42 RH_{12} +0.09 RH_{22} +1.07 SS_2 -0.14 RH_{13} +1.64 MT_3 -0.14 HTU_3 R^2 = 0.99
Branches per plant	-5.05-0.32 MT_1 +0.39 GDD_1 +1.03 MT_2 -1.04 GDD_2 -0.06 MIT_3 R^2 = 0.85
Green leaves	12.40-0.64 RH_{21} +0.032 SS_2 -0.037 HTU_2 R^2 = 0.81
Leaf area ($dm^2 m^2$)	-203.25-0.47 RH_{11} -1.06 RH_{12} +40.96 MT_2 -41.82 GDD_2 -0.17 HTU_2 +6.01 MAT_3 -1.12 RH_{13} -1.04 HTU_3 R^2 = 0.83
Leaf area index	-2.17+0.0067 RH_{21} +0.39 SS_1 -0.09 GDD_1 +0.016 RH_{22} +0.18 SS_2 +0.22 MAT_3 +0.0069 RH_{13} -0.60 SS_3 -0.17 GDD_3 R^2 = 0.87
Canopy dry weight	144.72-6.41 MAT_1 -3.51 RH_{11} +1.33 RH_{21} -9.53 RH_{12} +3.58 RH_{22} +48.55 SS_2 -3.84 HTU_2 -29.11 SS_3 +1.61 HTU_3 R^2 = 0.99
No. of pods per plant	24.67-2.29 MIT_1 +0.63 RH_{11} +6.79 SS_1 -3.37 MAT_2 +0.32 HTU_2 +4.17 MAT_3 -10.42 SS_3 -0.35 HTU_3 R^2 = 0.95
Seeds per pod	7.47-0.09 SS_1 -0.08 MAT_2 -0.04 RH_{12} +0.10 MAT_3 -0.01 RH_{13} -0.01 HTU_3 R^2 = 0.96
100 seed weight	-2.02-0.07 RH_{11} +0.03 RH_{21} +0.26 SS_1 +0.68 MAT_2 +0.08 RH_{22} -0.67 GDD_2 +0.02 RH_{13} -0.022 MT_3 -0.013 HTU_3 R^2 = 0.99
Harvest index	24.39-0.22 RH_{11} +0.06 RH_{21} -0.12 MT_1 +1.75 MAT_2 -0.20 RH_{12} +0.24 RH_{22} -1.64 GDD_2 +0.55 MAT_3 -0.10 HTU_3 R^2 = 0.99
Yield	1899+1.27 RH_{23} -5.63 HTU_3 R^2 = 0.77

ABBREVIATIONS

MAT_1 – Maximum temperature in phase 1
MAT_2 – Maximum temperature in phase 2
MAT_3 – Maximum temperature in phase 3
MIT_1 – Minimum temperature in phase 1
MIT_2 – Minimum temperature in phase 2
MIT_3 – Minimum temperature in phase 3
MT_1 – Mean temperature in phase 1
MT_2 – Mean temperature in phase 2
MT_3 – Mean temperature in phase 3
RH_{11} – Relative humidity in the morning in phase 1
RH_{12} – Relative humidity in the morning in phase 2
RH_{13} – Relative humidity in the morning in phase 3
RH_{21} – Relative humidity in the evening in phase 1
RH_{22} – Relative humidity in the evening in phase 2
RH_{23} – Relative humidity in the evening in phase 3
SS_1 – Sunshine hours in phase 1
SS_2 – Sunshine hours in phase 2
SS_3 – Sunshine hours in phase 3
GDD_1 – Growing degree days in phase 1
GDD_2 – Growing degree days in phase 2
GDD_3 – Growing degree days in phase 3
HTU_1 – Heliothermal units in phase 1
HTU_2 – Heliothermal units in phase 2
HTU_3 – Heliothermal units in phase 3

h. Descriptive model: A descriptive model defines the behaviour of a system in a simple manner. The model reflects little or none of the mechanisms that are the causes of phenomena. But, consists of one or more mathematical equations. An example of such an equation is the one derived from successively measured weights of a crop. The equation is helpful to determine quickly the weight of the crop where no observation was made.

i. Explanatory model: This consists of quantitative description of the mechanisms and processes that cause the behaviour of the system. To create this model, a system is analyzed and its processes and mechanisms are quantified separately. The model is built by integrating these descriptions for the entire system. It contains descriptions of distinct processes such as leaf area expansion, tiller production, etc. Crop growth is a consequence of these processes.

WEATHER DATA FOR MODELING

The national meteorological organizations provide weather data for crop modeling purposes through observatories across the globe (Sivakumar *et al.*, 2000). In many European countries weather records are available for over 50 years. In crop modeling the use of meteorological data has assumed a paramount importance. There is a need for high precision and accuracy of the data. The data obtained from surface observatories has proved to be excellent. It gained the confidence of the people across the globe for decades. These data are being used daily by people from all walks of life. But, the automated stations are yet to gain popularity in the under developed and developing countries. There is a huge gap between the old time surface observatories and present generation of automated stations with reference to measurement of rainfall. The principles involved in the construction and working of different sensors for measuring rainfall are not commonly followed in automated stations across the globe. As of now, solar radiation, temperature and precipitation are used as inputs in DSSAT.

Weather as an Input in Models

In crop modeling weather is used as an input. The available data ranges from one second to one month at different sites where crop-modeling work in the world is going on. Different curve fitting techniques, interpolation, extrapolation functions etc., are being followed to use weather data in the model operation. Agrometeorological variables are especially subject to variations in space. It is reported that, as of now, anything beyond daily data proved unworthy as they are either over-estimating or under-estimating the yield in simulation. Stochastic weather models can be used as random number generators whose input resembles the weather data to which they have been fit. These models are convenient and computationally fast, and are useful in a number of applications where the observed climate record is inadequate with respect to length, completeness, or spatial coverage. These applications include simulation of crop growth, development and impacts of climate change. In 1995 JW Jones and Thornton described a procedure to link a third-order Markov Rainfall model to interpolated monthly mean climate surfaces. The constructed surfaces were used to generate daily weather data (rainfall and solar radiation). These are being used for purposes of system characterization and to drive a wide variety of crop and live stock production and ecosystem models. The present generation of crop simulation models particularly DSSAT suit of models have proved their superiority over analytical, statistical, empirical, combination of two or all etc., models so far available. In the earliest crop simulation models only photosynthesis and carbon balance were simulated. Other processes such as vegetative and reproductive development, plant water balance, micronutrients, pest and disease, etc., are not accounted for as the statistical models use correlative approach and make large area yield prediction and only final yield data are correlated with the regional mean weather variables. This approach has slowly been replaced by the present simulation models by these DSSAT models. When many inputs are added in future the models become more complex. The modelers who attempt to obtain input parameters required to add these inputs look at weather as their primary concern. They may have to adjust to the situation where they develop capsules with the scale level at which the input data on weather are available.

Role of Weather in Decision Making

Decisions based solely upon mean climatic data are likely to be of limited use for at least two reasons. The first is concerned with definition of success and the second with averaging and time scale. In planning and analyzing agricultural systems it is essential not only to consider variability, but also to think of it in terms directly relevant to components of the system. Such analyses may be relatively straightforward probabilistic analyses of particular events, such as the start of cropping seasons in West Africa and India. The principal effects of weather on crop growth and development are well understood and are predictable. Crop simulation models can predict responses to large variations in weather. At every point of application weather data are the most important input. The main goal of most applications of crop models is to predict commercial out-put (Grain yield, fruits, root, biomass for fodder etc.). In general the management applications of crop simulation models can be defined as: 1) strategic applications (crop models are run prior to planting), 2) practical applications (crop models are run prior to and during crop growth) and 3) forecasting applications (models are run to predict yield both prior to and during crop growth).

Crop simulation models are used in USA and in Europe by farmers, private agencies, and policy makers to a greater extent for decision making. Under Indian and African climatic conditions these applications have an excellent role to play. The reasons being the dependence on monsoon rains for all agricultural operations in India and the frequent dry spells and scanty rainfall in crop growing areas in Africa. Once the arrival of monsoon is delayed the policy makers and agricultural scientists in India are under tremendous pressure. They need to go for contingency plans. These models enable to evaluate alternative management strategies, quickly, effectively and at no/low cost. To account for the interaction of the management scenarios with weather conditions and the risk associated with unpredictable weather, the simulations are conducted for at least 20-30 different weather seasons or weather years. If available, the historical weather data, and if not weather generators are used presently. The assumption is that these historical data will represent the variability of the weather conditions in future. Weather also plays a key role as input for long-term crop rotation and crop sequencing simulations.

CLIMATE CHANGE AND CROP MODELING

Climate change

Climate change is defined as "Any long term substantial deviation from present climate because of variations in weather and climatic elements".

The causes of climate change

1. The natural causes like changes in earth revolution, changes in area of continents, variations in solar system, etc.

2. Due to human activities the concentrations of carbon dioxide and certain other harmful atmospheric gases have been increasing. The present level of carbon dioxide is 325 ppm and it is expected to reach 700 ppm by the end of this century, because of the present trend of burning forests,

grasslands and fossil fuels. Few models predicted an increase in average temperature of 2.3 to 4.6°C and precipitation per day from 10 to 32 per cent in India.

Green house effect

The effect because of which the earth is warmed more than expected due to the presence of atmospheric gases like carbon dioxide, methane and other tropospheric gases. The shortwave radiation can pass through the atmosphere easily, but, the resultant outgoing terrestrial radiation can not escape because atmosphere is opaque to this radiation and this acts to conserve heat which rises temperature.

Effects of climate Change

1. The increased concentration of carbon dioxide and other green house gases are expected to increase the temperature of earth.

2. Crop production is highly dependent on variation in weather and therefore any change in global climate will have major effects on crop yields and productivity.

3. Elevated temperature and carbon dioxide affects the biological processes like respiration, photosynthesis, plant growth, reproduction, water use etc. In case of rice increased carbon dioxide levels results in larger number of tillers, greater biomass and grain yield. Similarly, in groundnut increased carbon dioxide levels results in greater biomass and pod yields.

4. However, in tropics and sub-tropics the possible increase in temperatures may offset the beneficial effects of carbon dioxide and results in significant yield losses and water requirements.

Proper understanding of the effects of climate change helps scientists to guide farmers to make crop management decisions such as selection of crops, cultivars, sowing dates and irrigation scheduling to minimize the risks.

Role of Climate Change in Crop Modeling

In recent years there has been a growing concern that changes in climate will lead to significant damage to both market and non-market sectors. The climate change will have a negative effect in many countries. But farmers adaptation to climate change-through changes in farming practices, cropping patterns, and use of new technologies will help to ease the impact. The variability of our climate and especially the associated weather extremes is currently one of the concerns of the scientific as well as general community. The application of crop models to study the potential impact of climate change and climate variability provides a direct link between models, agrometeorology and the concerns of the society. Tables 2 and 3 present the results of sensitivity analysis for different climate change scenarios for peanut in Hyderabad, India. As climate change deals with future issues, the use of General Circulation Models (GCMs) and crop simulation models proves a more scientific approach to study the impact of climate change on agricultural production and world food security compared to surveys.

Cropgro (DSSAT) is one of the first packages that modified weather simulation generators/or introduced a package to evaluate the performance of models for climate change situations. Irrespective of the limitations of GCMs it would be in the larger interest of farming community of the world that these DSSAT modelers look at GCMs for more accurate and acceptable weather generators for use in models. This will help in finding solutions to crop production under climate changes conditions, especially in underdeveloped and developing countries.

FUTURE ISSUES RELATED TO WEATHER ON CROP MODELING

For any application of a crop model weather data is an essential input and it continues to play a key role. So:

1. There is an urgent need to develop standards for weather station equipment and sensors installation and maintenance.

2. It is also important that a uniform file format is defined for storage and distribution of weather data, so that they can easily be exchanged among agrometeorologists, crop modelers and others working in climate and weather aspects across the globe.

3. Easy access to weather data, preferably through the internet and the world wide web, will be critical for the application of crop models for yield forecasting and tactical decision making.

4. Previously one of the limitations of the current crop simulation models was that they can only simulate crop yield for a particular site. At this

Table 2. Results of sensitivity analysis for different climate change scenarios showing the simulated mean peanut seed yield (kg ha^{-1}) at maturity and standard deviation (SD) for 25 years (1975-1999) of weather under irrigated and rainfed conditions at Hyderabad, India

Temperature increase (°C)	Irrigated				Rainfed			
	330 ppm CO_2		555 ppm CO_2		330 ppm CO_2		555 ppm CO_2	
	Yield	SD	Yield	SD	Yield	SD	Yield	SD
0.0	1570	112	2223	144	1431	219	2041	297
1.0	1526	120	2168	157	1369	234	1977	319
1.5	1484	119	2127	153	1322	224	1926	318
2.0	1451	130	2100	173	1294	236	1891	330
2.5	1436	132	2095	178	1274	240	1876	334
3.0	1437	134	2104	192	1260	251	1857	359
3.5	1450	139	2115	195	1187	354	1749	510
4.0	1210	551	1754	797	1060	480	1560	699
4.5	741	735	1077	1064	770	589	1148	869
5.0	377	621	555	916	530	560	662	818

Table 3. Results of sensitivity analysis for different climate change scenarios showing the simulated mean peanut seed yield (kg ha^{-1}) at maturity and standard deviation (SD) for 25 years (1975-1999) of weather under rainfed conditions at Hyderabad, India with 20% increase or decrease in rainfall

Temperature increase (ºC)	Rainfed (+20 % rainfall)				Rainfed (-20 % rainfall)			
	330 ppm CO_2		555 ppm CO_2		330 ppm CO_2		555 ppm CO_2	
	Yield	SD	Yield	SD	Yield	SD	Yield	SD
0.0	1494	106	2140	129	1430	219	1948	354
1.0	1437	95	2060	117	1298	294	1873	380
1.5	1400	88	2018	114	1254	283	1821	378
2.0	1368	82	1990	110	1222	295	1780	394
2.5	1356	82	1980	122	1195	295	1762	416
3.0	1367	93	2005	135	1177	315	1742	440
3.5	1385	106	2035	157	1095	394	1628	556
4.0	1346	301	1971	444	1015	452	1518	646
4.5	1238	475	1795	693	700	563	1048	830
5.0	1000	640	1213	1016	416	493	647	764

site weather (soil and management) data also must be available. It is a known fact that the weather data (and all these other details) are not available at all locations where crops are grown. To solve these problems the Geographical Information System (GIS) approach has opened up a whole field of crop modeling applications at spatial scale. From the field level for site-specific management to the regional level for productivity analysis and food security the role of GIS is going to be tremendous (Hoogenboom, 2000).

APPLICATIONS AND USES OF CROP GROWTH MODELS IN AGRICULTURAL METEOROLOGY

The crop growth models are being developed to meet the demands under the following situations in agricultural meteorology.

1. When the farmers have the difficult task of managing their crops on poor soils in harsh and risky climates.

2. When scientists and research managers need tools that can assist them in taking an integrated approach to finding solutions in the complex problem of weather, soil and crop management.

3. When policy makers and administrators need simple tools that can assist them in policy management in agricultural meteorology.

The potential uses of crop growth models for practical applications are as follows (Sivakumar and Glinni, 2000).

On farm decision-making and agronomic management

The models allow evaluation of one or more options that are available with respect to one or more agronomic management decisions like:

- Determine optimum planting date.
- Determine best choice of cultivars.
- Evaluate weather risk.
- Investment decisions.

The crop growth models can be used to predict crop performance in regions where the crop has not been grown before or not grown under optimal conditions. Such applications are of value for regional development and agricultural planning in developing countries (Van Keulen and Wolf, 1986). A model can calculate probabilities of grain yield levels for a given soil type based on rainfall (Kiniry and Bockhot, 1998). Investment decisions like purchase of irrigation systems (Boggess and Amerling, 1983) can be taken with an eye on long term usage of the equipment thus acquired. Kiniry *et al.* (1991) showed that for maize, both simulated and measured mean yields with weeds are 86% of the weed-free yields.

Understanding of research

In agro-meteorological research the crop models basically helps in:

- Testing scientific hypothesis.
- Highlight where information is missing.
- Organizing data.
- Integrating across disciplines.
- Assist in genetic improvement;
  - Evaluate optimum genetic traits for specific environments.
  - Evaluate cultivar stability under long term weather.

Penning de Vries (1977) emphasized that simulation models contribute to our understanding of the real system which in-turn helps to bridge areas and levels of knowledge. It is believed that in conversion of conceptual models into mathematical simulation models the agrometeorologists can understand the gaps in their knowledge. So, the interdisciplinary nature of simulation modeling efforts leads to increased research efficacy and improved research direction through direct feedback. In this direction de Wit and Goudriaan (1978) developed BAsic CROp growth Simulator (BACROS) which was used as a reference model for developing other models and as a basis for developing summary models. Also O Toole and Stockle (1987) described the potential of simulation models in assessing trait benefits of winter cereals and their capacity to survive and reproduce in stress-prone environment. Crop growth models have been used in plant breeding to simulate the effects of changes in the morphological and physiological characteristics of crops which aid in identification of ideotypes for different environments (Hunt, 1993; Kropff *et al.*, 1995).

Policy management

The policy management is one very useful application of crop simulation models. The issues range from global (impacts of climate change on crops) to field level (effect of crop rotation on soil quality) issues. Thornton *et al.* (1997) showed that in Burkina Faso, crop simulation modeling using satellite and ground-based data could be used to estimate millet production for famine early warning which can allow policy makers the time they need to take appropriate steps to ameliorate the effects of global food shortages on vulnerable urban and rural populations. In Australia Meinke and Hammer (1997) found that when November-December SOI (Southern Oscillation Index) phase is positive, there is an 80% chance of exceeding average district yields. Conversely, in years when the November-December SOI phase is either negative or rapidly falling, there is only a 5% chance of exceeding average district yields, but a 95% chance of below average yields. This information allows the industry to adjust strategically for the expected volume of production.

Crop models can be used to understand the effects of climate change such as :

a) Consequences of elevated carbon-dioxide, and

b) Changes in temperature and rainfall on crop development, growth and yield. Ultimately, the breeders can anticipate future requirements based on the climate change.

A FEW SUCCESSFULLY USED MODELS IN AGROMETEOROLOGY

Large scale evolution of computers since 1960 allowed to synthesize detailed knowledge on plant physiological processes in order to explain the functioning of crops as a whole. Insights into various processes were expressed using mathematical equations and integrated in simulation models. In the beginning, models were meant to increase the understanding of crop behaviour by explaining crop growth and development in terms of the understanding physiological mechanisms. Over the years new insights and different research questions motivated the further development of simulation models. In addition to their explanatory function, the applicability of well-tested models for extrapolation and prediction was quickly recognized and more application-oriented models were developed. For instance demands for advisory systems for farmers and scenario studies for policy makers resulted in the evolution of models, geared towards tactical and strategic decision support respectively.

Now, crop growth modeling and simulation have become accepted tools for agricultural research.A few models used in agrometeorological studies are:

1. The de Wit school of models

In the sixties, the first attempt to model photosynthetic rates of crop canopies was made (de Wit, 1965). The results obtained from this model were used among others, to estimate potential food production for some areas of the world and to provide indications for crop management and breeding (de Wit, 1967; Linneman *et al.*, 1979). This was followed by the construction of an Elementary CROp growth Simulator (ELCROS) by de Wit *et al.* (1970). This model included the static photosynthesis model and crop respiration was taken as a fixed fraction per day of the biomass, plus an amount proportional to the growth rate. In addition, a functional equilibrium between root and shoot growth was added (Penning de Vries *et al.*, 1974). The introduction of micrometeorology in the models (Goudriaan, 1977) and quantification of canopy resistance to gas exchanges allowed the models to improve the simulation of transpiration and evolve into the BAsic CROp growth Simulator (BACROS) (de Wit and Goudriaan, 1978).

2. IBSNAT and DSSAT Models

In many countries of the world, agriculture is the primary economic activity. Great numbers of the people depend on agriculture for their livelihood or to meet their daily needs, such as food. There is a continuous pressure to improve agricultural production due to staggering increase in human population. Agriculture is very much influenced by the prevailing weather and climate. The population increase is 2.1 per cent in India. This demands a systematic appraisal of climatic and soil resources to recast an effective land use plan. More than ever farmers across the globe want access to options such as the management options or new commercial crops. Often, the goal is to obtain higher yields from the crops that they have been growing for a long time. Also, while sustaining the yield levels they want to :

1. Substantially improve the income.
2. Reduce soil degradation.
3. Reduce dependence on off-farm inputs.
4. Exploit local market opportunities.

5. Farmers also need a facilitating environment in which;
   a. Affordable credit is available.
   b. Policies are conducive to judicious management of natural resources.
   c. Costs and prices of production are stable.

6 Another key ingredient of a facilitating environment is information, such as :
   a. An understanding of which options are available.
   b. How these operate at farm level.
   c. The impact on issues of their priority.

To meet the above requirements of resource poor farmers in the tropics and sub tropics IBSNAT (International Benchmark Sites Network for Agro-technology Transfer) began in 1982. This was under a contract from the U.S. Agency for International Development to the University of Hawaii at Manoa, USA. IBSNAT was an attempt to demonstrate the effectiveness of understanding options through systems analysis and simulation for ultimate benefit of farm households across the globe. The purposes defined for the IBSNAT project by its technical advisory committee were to :

1. Understand ecosystem processes and mechanisms.
2. Synthesize from an understanding of processes and mechanisms, a capacity to predict outcomes.
3. Enable IBSNAT clientele to apply the predictive capability to control outcomes.

The models developed by IBSNAT were simply the means by which the knowledge scientists have and could be placed in the hands of users. In this regard, IBSNAT was a project on systems analysis and simulation as a way to provide users with options for change. In this project many research institutions, universities, and researchers across the globe spent enormous amount of time and resources and focused on:

1 Production of a “decision support system” capable of simulating the risks and consequences of alternative choices, through multi-institute and multi-disciplinary approaches.

2. Definition of minimum amount of data required for running simulations and assessing outcomes.

3. Testing and application of the product on global agricultural problems requiring site-specific yield simulations.

The major product of IBSNAT was a Decision Support System for Agro-Technology Transfer (DSSAT). The network members lead by J.W. Jones, Gainesville, USA developed this. The DSSAT is being used as a research and teaching tool. As a research tool its role to derive recommendations concerning crop management and to investigate environmental and sustainability issues is unparalleled. The DSSAT products enable users to match the biological requirements of crops to the physical characteristics of land to provide them with management options for improved land use planning. The DSSAT is being used as a business tool to enhance profitability and to improve input marketing.

The traditional experimentation is time consuming and costly. So, systems analysis and simulation have an important role to play in fostering this understanding of options. The information science is rapidly changing. The computer technology is blossoming. So, DSSAT has the potential to reduce substantially the time and cost of field experimentation necessary for adequate evaluation of new cultivars and new management systems. Several crop growth and yield models built on a framework similar in structure were developed as part of DSSAT package. The package consists of : 1) data base management system for soil, weather, genetic coefficients, and management inputs, 2) Crop-simulation models, 3) series of utility programs, 4) series of weather generation programs, 5) strategy evaluation program to evaluate options including choice of variety, planting date, plant population density, row spacing, soil type, irrigation, fertilizer application, initial conditions on yields, water stress in the vegetative or reproductive stages of development, and net returns.

Other Important Models

Crop models can be developed at various levels of complexity. The level of complexity required depends on the objective of the modeling exercise. The top-down approach to model design (Hammer *et al.*, 1989; Shorter *et al.*, 1991) is appropriate for models aimed at yield prediction. In this approach, complexity is kept to a minimum by commencing with a simple framework and only incorporating additional phenomena or processes if they improve the predictive ability of the model. Sinclair (1986), Muchow *et al*. (1990) and Hammer and Muchow (1991) have adopted this method in developing models of soybean, maize and sorghum respectively.

The EPIC, ALAMANC, CROPSYST, WOFOST, ADEL models are being successfully used to simulate maize crop growth and yield. The SORKAM, SorModel, SORGF as also ALMANAC models are being used to address specific tasks of sorghum crop management. CERES – pearl millet model, CROPSYST, PmModels are being used to study the suitability and yield simulation of pearl millet genotypes across the globe. Similarly, the two most common growth models used in application for cotton are the GOSSYM and COTONS models. On the same analogy the PNUTGRO for groundnut, CHIKPGRO for chick pea, WTGROWS for wheat, SOYGRO for soybean, QSUN for sunflower are in use to meet the requirements of farmers, scientists, decision makers, etc., at present. The APSIM, GROWIT added with several modules are being used in crop rotation, crop sequence and simulation studies involving perennial crops.

Under Indian sub-continent conditions, crop yield forecasting based on meteorological data is very important from several points of view. Using crop yield as dependent variable and weather factors as independent variables, empirical statistical models for predicting crop yield have been reported by Mall *et al*. (1996). Also, Mall and Gupta (2000) reported a successful empirical statistical – yield weather model for wheat in the Varanasi district of Uttar Pradesh, India. Rajesh Kumar *et al*. (1999) developed a stepwise regression model which states that the pigeonpea yield variation by weather variables is upto 94 per cent in Varanasi District, U.P., India. Using a thermal time and phasic development model. Patel *et al.* (1999) found that pigeonpea phenophases depended upon the available heat units and accounted for 98 per cent of total variation in Anand, Gujarat State, India.

Elsewhere in the world there were studies (Robertson and Foong, 1977; Foong, 1981), which predicted yields based on climatic factors using mathematical modeling. Factors such as water deficit, solar radiation, maximum and minimum temperatures which play a vital role at floral initiation were taken into consideration to construct these models. In Southern Malaysia Ong (1982) found a high correlation between yield of oil palm and rainfall and dry spells as also temperature and sunshine using a step-wise regression approach. Chow (1991) constructed a statistical model for predicting crude palm oil production with trend, season, rainfall, etc. Amissah-Arthur and Jagtap

(1995) successfully assessed nitrogen requirements by maize across agro ecological zones in Nigeria using CERES-maize model. Hammer *et al*. (1995) using local weather and soil information correlated peanut yields with estimates from PEANUTGRO, a model in the CERES family and gave a regression with high coefficient (r^2 = 0.93) of variation. The construction of contemporary crop models entails the combination of many algorithms for physiological processes and impact of environmental factors on process rates (Monteith, 2000). This clearly indicates that in the development of models and their application for solving problems at field level on agrometeorological aspects are given due weightage.

APPLICATION OF MODELS IN AGRICULTURAL METEOROLOGY – PRECAUTIONS

Hunger demands food. Food grains come from agriculture, but it is risk-prone. So research efforts are necessary. Unfortunately, funding for research worldwide is declining at an alarming rate. The agricultural scientists and planners are facing formidable challenges to ensure continued increases in agricultural productivity to meet the food grain requirements of burgeoning population across the globe. Nowadays, the traditional field experimentation is becoming very expensive. So, the works on development and use of crop growth models to answer strategic and tactical questions concerning agricultural planning as well as on-farm soil and crop management are essential.

Although these models are useful in more than one way as detailed earlier in this lecture, much of the modeling uses and applications to date have been mainly in the area of research. The products of research need to be disseminated to the farmers. Otherwise the present works on crop modeling cannot sustain in the long run. So far, much of crop modeling applications in the literature are based on sole cropping and only in the recent past this work has been extended to intercrops, crop rotations, crop sequences, etc. The works on crop rotations shall be taken up on priority. If one considers the attention given to individual crops so far maize and cotton rank more than 50% of the work but there are many other crops that meet food requirements of the population in tropical and sub-tropical areas of the world. So, it is essential to understand fully the physical and physiological processes of these crops that govern their growth and yield under valuable soil and climatic conditions through crop models.

The development of agrometerological and agroclimatological models include climate crop and soil. The availability of water (which is an observed parameter through rainfall) and water requirement (expressed by PET which is an estimated parameter) are basic inputs in majority of these studies. The suitability of individual models for the estimation of PET depends not only on accurate predictive ability of the model but also on the availability of necessary input data. In addition, the following points shall be taken into considerations in model development and their application as precautions in agricultural meteorological studies.

1. Adequate human resource capacity has to be improved to develop and validate simulation models across the globe.
2. Multi-disciplinary research activities are essential for qualitative works in crop growth modeling.
3. Linkages shall be made and strengthened among research – education – extension to quickly disseminate the outcomes of models to farmers.
4. Majority of models use rainfall data at monthly interval, which is too long a period when compared to short duration of dry land crops (Sorghum, pearlmillet mature in 100 days). So, there is an urgent need to correct this anomaly by selecting proper methodologies.
5. It is important to differentiate between models of interest for research and for practical application. So, models useful to farmers with minimum input parameters shall find right place in the society.
6. It is always preferable to use one or more methods / models in conjunction to get more realistic conclusions useful to the farmers, who are the ultimate beneficiary alongwith industries.
7. The requirements in terms of details for local agricultural planning and operations are quite different from regional agricultural planning. Therefore, while selecting / using any model, it must be kept in mind the clear objective of study on one hand and verifying with ground truth (irrespective of the claims of the modal author) on the other hand.
8. The results / output of the models must be interpreted in an appropriate way by integrating soil, weather and crop. This interpretation is the key for success of agrometerological models. So, application of crop growth models shall form a part of studies of agrometeorologists on a regular and more continuous basis.

9. One should trust contemporary models particularly those concerned with yields. Wide variations may be found in the yield predicted by different models for specific crop in a defined environment. There is a need to develop test and improve the models with similar basis till they achieve comparable success for use by farmers, extension workers industry, etc. The reason is that the farmer needs them for decision-making, because It was found that the model can be used to identity new sites suitable for development of crop which finally results in generation of income to them.

10. It will be important to link the crop simulation models to local short and long-term weather forecasts. This will improve the yield predictions and provide policy makers with advanced yield information to help manage expected famines and other associated problems.

CONCLUSIONS

Various kinds of models such as Statistical, Mechanistic, Deterministic, Stochastic, Dynamic, Static, Simulations are in use for assessing and predicting crop growth and yield. Crop growth model is a very effective tool for predicting possible impacts of climatic change on crop growth and yield. Crop growth models are useful for solving various practical problems in agriculture. Adequate human resource capacity has to be improved to be develop and validate simulation models across the globe.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the excellent encouragement, technical review and recommendations provided by Dr. M.V.K. Sivakumar, Professor C.J. Stigter, Professor Gerrit Hoogenboom and Dr. P.V.V. Prasad in preparation of the manuscript.

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